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(54) Ultrsonic testing method and apparatus

(57) An ultrasound transducer 16 is coupled to a workpiece 10 by an elastomeric member 18 and measurements based on echoes returned from inhomogenities within the workpiece are initiated by detection of the echo from the interface between the workpiece and the coupling member. The device is particularly suited for measuring the extensions, and and hence stressed in a bolt, while the compliant nature of the coupling member allows effective coupling even in the presence of surface irregularities such as the raised grade markings 14, on the bolt head 12.

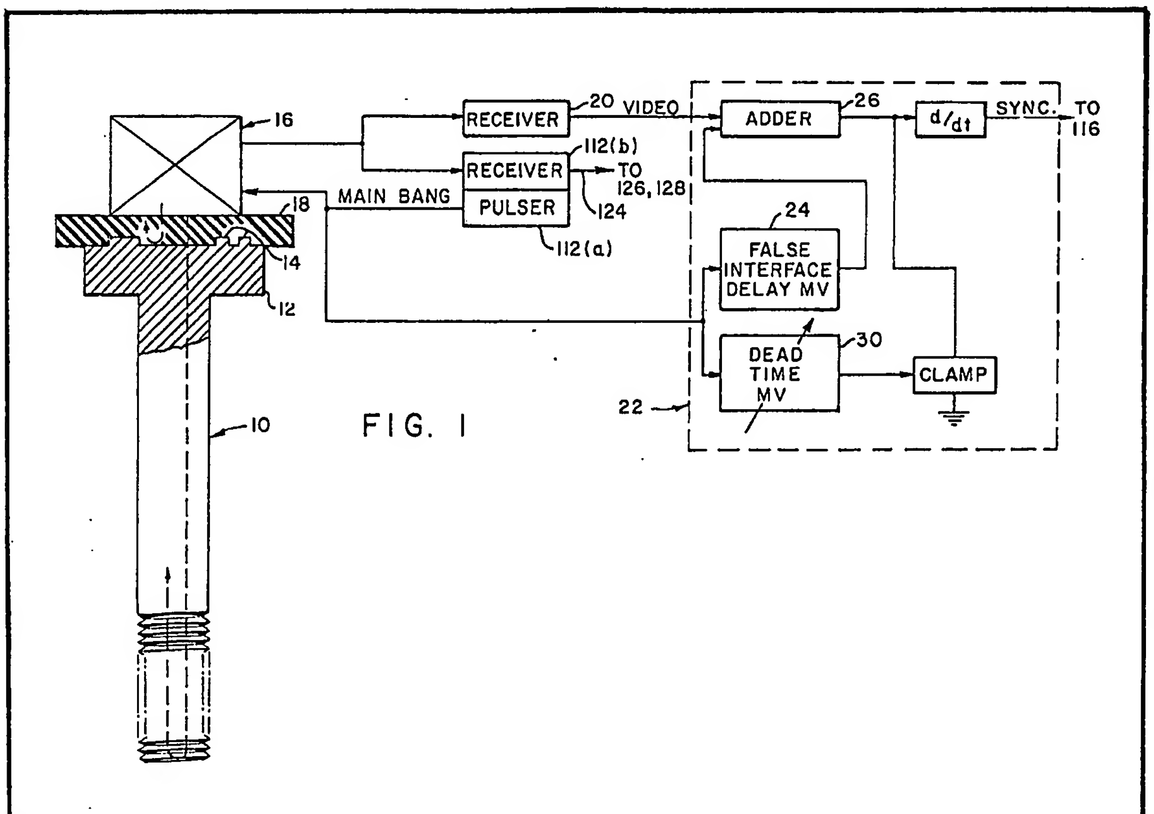

FIG. 1

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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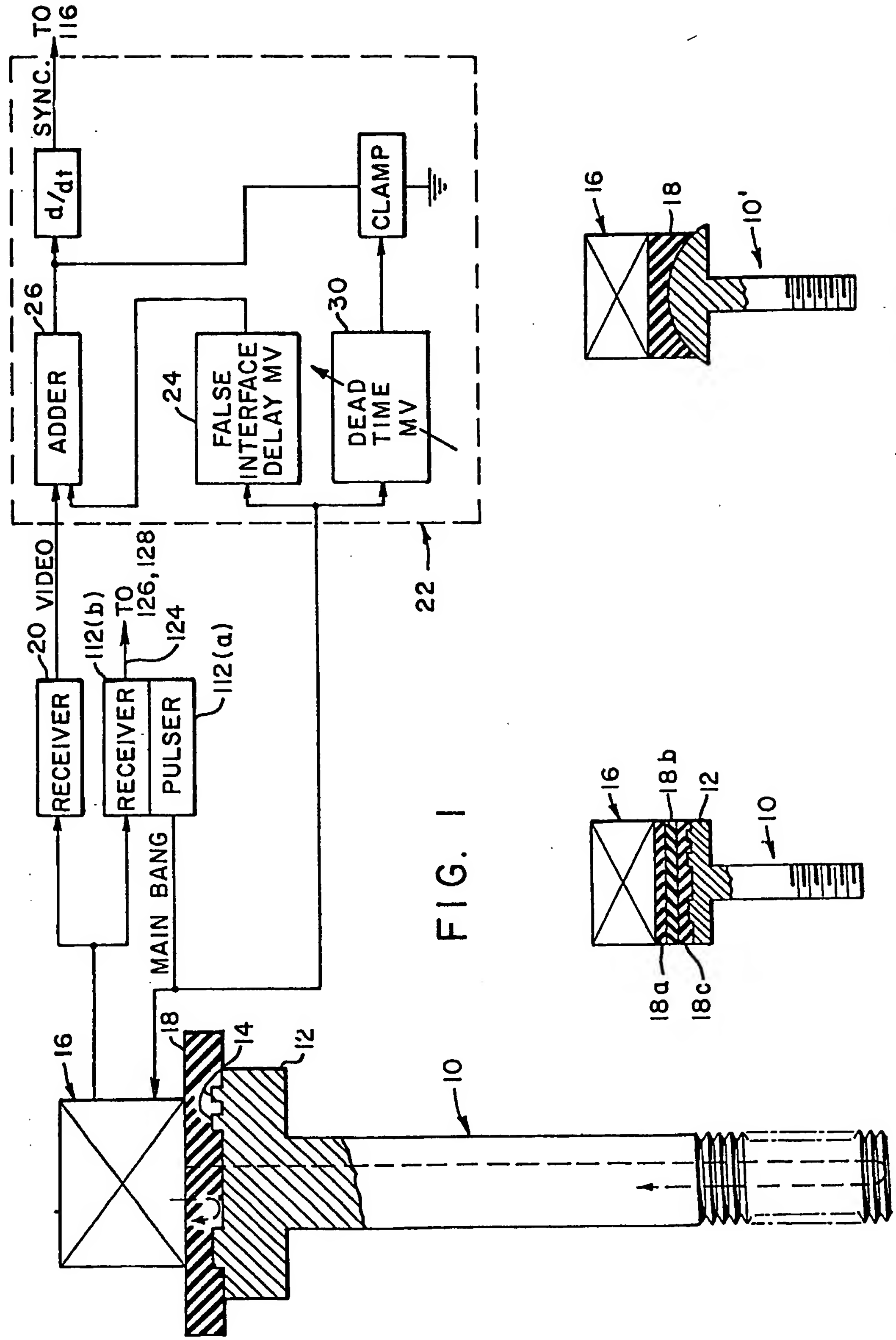

FIG. 1

FIG. 2

FIG. 3

SPECIFICATION

Ultrasonic testing method and apparatus

The present invention relates to non-destructive testing and particularly to the use of ultrasonic energy to measure the length or thickness of a workpiece. More especially, this invention is directed to ultrasonic testing methods and apparatus for precise measurement wherein the ultrasound transducer is coupled to the workpiece via a dry resilient coupling member which presents a short path length to the ultrasound energy. Accordingly, the general objects of the present invention are to provide novel and improved methods and apparatus of such character.

While not limited thereto in its utility, the present invention is particularly well suited for use in the measurement of dimensional changes in metallic workpieces which are subject to mechanical loading. One class of apparatus employed in the making of such measurements are known as extensometers. Ultrasonic extensometers which have achieved significant commercial success are described in U.S Patents 3,759,090 and 3,810,385. An extensometer is a precision instrument that can be used to measure bolt length and thus can be employed to measure the stretch in a bolt under tension. Whenever a bolt is tightened or stressed, it is stretched and the degree of dimensional change in the direction of the length of the bolt may thus be a measure of how tight the bolt is.

In order for a bolt length measurement to be performed with an ultrasonic extensometer, it is necessary that the ultrasound transducer associated with the extensometer be coupled to the bolt and this coupling is typically to the bolt head since the head is usually the most accessible portion of the bolt. In the prior art two coupling techniques have been successfully employed. Firstly, as depicted in the above referenced patents, a film of oil or glycerine can be placed on the bolt head and the transducer then urged into direct contact with the bolt head either with the aid of magnets or mechanical fasteners. Many bolts, however, are provided with raised grade markings on the bolt head and such grade markings must be removed if such a direct coupling technique is to be employed. The removal of the grade markings from a bolt head, however, is undesirable for numerous reaons, not the least of which is the fact that such removal is a time consuming task. Secondly, it has been proposed to couple the transducer to the bolt head via a liquid. This, however, has been found to be an impractical approach since the acoustic path length in the liquid must be made sufficiently long so that the reverberation in the liquid path occurs after the echos of interest have been received back at the transducer from the bolt. That is, an acoustic delay which is longer than the acoustic length of the part being examined must be established when liquid coupling is employed. Liquid coupling is, accordingly, an unwieldy technique and in many instances the location of the bolt to be measured precludes its use. Thus, in the prior art the use of liquid coupling of ultrasonic energy from a transducer to a workpiece has largely been limited to those situations where the workpiece could be immersed in a bath for inspection.

The use of dry coupling members between an ultrasound transducer and a workpiece has also been proposed but not previously successfully implemented in the field of extensometry. This lack of prior success, in part, may be attributed to the previous inability to achieve the desired matching of the acoustic impedances of the bolt or other workpiece to the coupling member and transducer. Also, in the extensometer environment, a usable coupling medium would have to be sufficiently resilient to permit the grade markings on the bolt head to become embedded therein. A dry coupling medium must also meet the contradictory requirements that it be active enough to couple sufficient ultrasound energy into the bolt or other workpiece so that a detectable echo will be reflected from the most distant end of the bolt while it must also be sufficiently lossy so that reverberation in the coupling medium will not be confused with the echo from the end of the bolt. Coupling mediums meeting all of these operating characteristics have not previously been suggested and thus, as noted, resort has been either to direct coupling or long path length liquid coupling.

The purpose of the invention is to overcome the above briefly discussed and other deficiencies and disadvantages of the prior art by providing a thin compliant dry coupling for use between an ultrasound transducer and a workpiece. This invention also encompasses a unique measuring technique, and apparatus for use therein, which enables the use of this dry couplant.

In accordance with the present invention there is provided a method for the non-destructive testing of workpieces comprising the steps of:

positioning a dry compliant couplant between an ultrasound transducer and a workpiece, non-planar surface features on the workpiece being embedded in the couplant whereby the transmission axis of the transducer will remain substantially transverse to a plane defined by the average surface of the workpiece;

exciting the transducer to cause generation thereby of a burst of ultrasonic energy, the ultrasonic energy being directed through the couplant into the workpiece and being reflected from inhomogeneities encountered along the transmission axis;

detecting energy reflected from inhomogeneities in the ultrasound transmission path;

identifying the echo commensurate with energy reflected from the couplant/workpiece interface;

disregarding echos received prior to identification of the echo from the couplant/workpiece interface; and

employing echos received after the identification of the echo from the couplant/workpiece interface to determine a parameter of the workpiece.

There is also provided an apparatus for use in the non-destructive testing of workpieces comprising:

transducer means responsive to an excitation signal for generating ultrasonic energy, the ultrasonic energy being radiated along an axis, said transducer means also generating signals commensurate with echos corresponding to the reflection of ultrasonic energy form inhomogeneities encountered along the said axis;

dry coupling means positioned between the workpiece and said transducer means, and ultrasound energy passing through said coupling means, said coupling means being sufficiently compliant so that workpiece surface features which extend above a plane transverse to the said axis will embed therein:

first receiver means responsive to echo signals generated by said transducer means for generating information bearing signals; and

second receiver means responsive to echo signals generated by said transducer means and to transducer excitation signals for generating timing control signals, said timing control and information bearing signals enabling the calculation of workpiece parameters of interest.

A dry couplant in accordance with the present invention is characterized by having sufficient compliancy to allow surface features on a workpiece, for example grade markings or the like on the head of a bolt, to embed therein whereby the couplant may properly perform the function of conducting the ultrasound energy to the bolt or other workpiece. Additionally, a couplant in accordance with the present invention is sufficiently thin and lossy to insure that the energy transmission axis of the transducer remains in its desired normal orientation to the workpiece; i.e., the couplant will not cause the transducer to tend to rock off a bolt head. The couplant will also be sufficiently thin so that multiple echoes in the couplant will die out before any echo is received from the far end of the workpiece. Additionally the couplant will be characterized by acoustic impedance which is sufficiently closely matched to the acoustic impedance of the workpiece and transducer to insure that efficient ultrasound energy transfer will occur and that reverberation will be reduced to an acceptable level. A couplant material in accordance with the invention may be loaded with materials which raise its density and increase its acoustic impedance so as to reduce reverberation. An acoustically lossy material may also be added to the couplant material help reduce reverberation in the couplant.

A test instrument in accordance with a preferred embodiment of the present invention includes means for detecting the echo received from the interface between the dry couplant and the workpiece. This interface echo signal is employed to start the timing for measurement of length or thickness of the workpiece. The use of an echo signal which is produced after the ultrasound energy has passed through the relatively thin and compliant couplant eliminates problems previously encountered with long liquid coupling paths. Thus, apparatus in accordance with the present invention is not affected by compression of the couplant and variations in the acoustic path length in the couplant will have no effect on the accuracy of the measurement.

The present invention may be better understood and its numerous objects and advantages will become apparent to those skilled in the art by reference to the accompanying drawing wherein:

Figure 1 is a functional block diagram which depicts apparatus in accordance with a preferred embodiment of the invention;

Figure 2 is a side elevation view depicting the use of a multilayer dry couplant in accordance with the invention; and

Figure 3 illustrates a dry couplant in accordance with the invention in the environment of a carriage-type bolt.

In order to facilitate understanding of the present invention, reference will be had to above-mentioned Patent 3,759,090 and particularly to Figures 4 and 5 thereof. Thus, in the discussion below, the relationship of a hardware embodiment of the present invention to the signal processing circuitry of Figure 4 of said Patent 3,759,090 will be explained.

Referring to Figure 1, a threaded fastener, the length of which is of interest, is indicated generally at 10. The fastener or bolt 10 has a head 12 which is accessible and which is engaged by a tightening tool, for example a torque wrench, whereby bolt 10 may be placed in tension and thus stretched. The head 12 of bolt 10 is provided with raised grade markings, indicated at 14. As explained in referenced Patent 3,759,090, the length of bolt 10 may be measured ultrasonically before and after tightening and the difference in length displayed. This difference in length will provide an indication of the tension in bolt 10.

In the prior art, as represented in Figure 1 of the referenced patent, an ultrasound transducer was placed in direct contact with the head of a bolt when it was desired to measure the length of that bolt. Such an ultrasonic transducer is indicated generally and schematically at 16 in Figure 1 of the present application. The requisite tight contact between the transducer and bolt was established and maintained through the use of a mechanical or magnetic holddown attachment which has been omitted from the drawing of the instant application but which may still be employed. In the prior art, as noted above, a film of oil or glycerine was employed to enhance the coupling of energy from the transducer to the bolt.

The energization of the transducer will produce a short burst of ultrasonic energy which, in the

prior art, is coupled across the transducer/bolt head interface and then travels the length of the bolt. The burst of ultrasonic energy, which is of sufficiently short duration to be considered a single pulse, will be reflected from any inhomogeneities in the bolt and, presuming that the bolt has no flaws, the first echo returned to transducer 16 will be from the far end of the bolt. This echo, i.e., the ultrasonic energy reflected back from the end of the bolt, will be reconverted by transducer 16 into an electrical signal which is supplied to a receiver for processing, a prior art receiver/signal processing circuit being is in Figure 4 of referenced Patent 3,759,090. Knowing the velocity of transmission of the ultrasonic energy in the particular workpiece, the length or thickness thereof will be a function of time it takes the ultrasound energy to travel completely through the workpiece and an echo to be returned from the opposite side thereof. Thus, in order to start the timing the receiver/signal processing circuitry of Patent 3,759,090 is responsive to the "main bang" signal employed to energize (excite) the ultrasound transducer. Since the transducer will "ring" when energized, this being a well known characteristic of piezoelectric transducers, the "main bang" signal will be briefly and uniformly delayed at the receiver so that the signal processing circuitry will not be responsive to signals associated with the "ringing", i.e., the signal processing circuit will not be enabled until sufficient time has elapsed for the "ringing" to die out.

Returning to a discussion of the present invention as depicted in Figure 1, it will be obvious that the grade markings 14 on the head 12 of bolt 10 will prevent the establishment of adequate direct contact between transducer 16 and the bolt to insure the coupling into bolt 10 of sufficient energy to produce a detectable echo from the far end of the bolt. Accordingly, a couplant must be employed between transducer 16 and bolt head 12. As discussed above prior art liquid path coupling techniques, where the coupling medium is thick enough so that reverberations from the couplant/bolt interface occur at a time subsequent to receipt of an echo from the end of the bolt, are not practical for many extensometer applications. In accordance with the present invention, a dry and compliant couplant 18 is employed. Since couplant 18 must work with fasteners having external grade markings, the material from which it is fabricated must be compliant so that the grade markings will embed in the couplant while the surface of the couplant disposed away from the bolt head will remain transverse to the bolt axis. The foregoing requires that the couplant be thicker than the raised grade markings which may be encountered. By the same token, the couplant must be acoustically active enough to couple sufficient ultrasound into bolt 10 so that the echo from the far end of the bolt will be strong enough to be detected; the acoustic impendance of the material comprising couplant 18 and its thickness affecting attenuation and the couplant thus being as thin as possible to meet the above stated criteria. Since reverberation from the couplant/bolt head interface will occur, the material comprising couplant 18 must have a sufficiently high acoustic impendance and be lossy enough so that the reverberation in the couplant will not be confused with the echo from the end of the bolt.

To summarize the above requirements, the couplant 18 must be resilient. It has been discovered that a resilient material having a Shore rating of between 20 and 60, and preferably between 25 and 45, is suitable if the thickness of the couplant 18 is in the range of 0.635 to 3.8mm. As a rule of thumb, the thickness of the couplant should be about twice the height of the grade marking or other surface projection or irregularity for which compensation must be made. It has been found that a thickness in the range of 0.635 to 1mm is sufficient to permit the grade markings on commercially available bolts to adequately embed in the couplant without interfering with the ultrasonic energy entering the main portion of the bolt. The dry couplant 18 in accordance with the present invention may be successfully fabricated from elastomeric materials such as Neoprene rubber, silicone rubber and gum rubber with particularly good results having been obtained with silicone rubber having Shore numbers in the range of 25 to 40 and pure gum rubber of Shore 40. It is preferable, but not essential, that the material comprising couplant 18 be capable of being cast directly on the face of transducer 16. It is also possible to load the material comprising couplant 18 to increase its acoustic impedance thereby effecting a fast damping of reverberation in the couplant while insuring a strong couplant/bolt interface echo and, of course, permitting sufficient energy to be coupled into the bolt so as to provide a strong echo from the end thereof. This loading of the couplant material may be accomplished by the addition of powdered metal to the elastomer. In accordance with a typical embodiment of the invention, the couplant is a disc of silicone rubber, ranging in diameter from 6.35 to 51mm and in thickness from 0.5 to 3.2mm which may be loaded with a powdered metal such as zinc, iron, nickel, aluminium or tungsten. In one reduction to practice the diameter of the unfilled silicone rubber disc was 25.5mm and its thickness was 3.2mm. This dry couplant was characterized by good sound transfer from the transducer into the bolt and quick ring down in the couplant material, i.e., the damping of the back and forth reverberations of the ultrasound within the couplant was quite short.

While this invention has been discussed relative to grade markings, it will be understood that the invention compensates for and is useable with any bolt head irregularities. Indeed, the invention can also be used with deliberately shaped parts, such as the carriage bolt depicted in Figure 3. As shown in Figure 3, the curvature of

the head of carriage bolt 10′ can be considered as, a projecting surface for which compensation must be made by the dry couplant 18.

In accordance with the present invention, the ultrasound round trip travel time from the transducer to the far end of the bolt will be a function of the pressure on the transducer. That is, the couplant 18 will compress when the transducer is pushed against its surface so as to cause roughness or grade markings on the head of the bolt to embed in the couplant. Accordingly, in employing the present invention it is not possible to preselect a delay time commensurate with the couplant thickness but rather the actual thickness of the compressed couplant must be taken into account. In the present invention this is accomplished by making all measurements from the front surface of the fastener, i.e., from the couplant/bolt head interface in the example shown in the drawing, rather than from the "main bang" as taught in referenced Patent 3,759,090. The preferred embodiment of the present invention, accordingly, employs a pair of receivers connected to transducer 16. The first of these receiver/signal processing circuits may be of the type depicted in Figure 4 of the said referenced Patent 3,759,090 with the exception that the "main bang" signal, shown in Figure 5 of the patent at 168, is disconnected from the monostable multivibrator 116 of Figure 4 of the said patent. Thus, as depicted in Figure 1 of the instant application, where the same reference numbers have been employed as used in Figure 4 of Patent 3,759,090 for like elements (with the exception of the transducer which is indicated at 16 in the instant application), there is no longer an output from pulser 112a delivered to the vernier delay multivibrator 116. Rather, the output signal provided by transducer 16 is simultaneously delivered to receiver 112b and to a new receiver 20. The output of receiver 20 is coupled via an interface logic circuit 22, to the vernier delay multivibrator 116. In the manner to be described below, the interface logic circuit 22 will recognize the first echo, commensurate with the front end of the bolt, and will provide a gating signal to multivibrator 116 which is commensurate with ultrasound energy produced by transducer 16 being coupled across the bolt face/couplant interface.

The receiver 20 is effectively an amplifier circuit which has sufficient gain to insure that a useable signal is provided for each received echo. The gain of receiver 20 may, however, be comparatively low since the signals of interest to this circuit are the echoes from the couplant/bolt interface. Conversely, since receiver 112b must be sensitive to echo signals received from the far end of the bolt, and there is of course attenuation as the ultrasonic energy traverses the length of the bolt and returns from the far end thereof, receiver 112b must be a high gain device which may include an automatic gain control. Receiver 20 may be operated with a manual gain control.

The interface logic circuit 22 receives the video signal from receiver 20 and the "main bang" signal from pulser 112a. The main bang signal is employed as a gating control input which enables the interface logic, in the manner to be described below, after a sufficient time delay, on the order of 1 microsecond, for ringing of the transducer to subside. The "main bang" signal also starts the timing of a "false interface" circuit 24 which generates what appears to the logic circuit 22 to be another echo. This false echo or interface signal will be added, in an adder 26, to any video signal appearing at the output of receiver 20, these video input signals being the actual echo signals. The echo signal of maximum amplitude will be that which is commensurate with the couplant/bolt interface.

The function of interface circuit 22 is to convert the video signal from receiver 20 into a short duration synchronization pulse which, when applied to the vernier delay multivibrator 116, will turn on the clock of the extensometer when an echo is received from the front surface of the bolt 10. This synchronization pulse is produced by differentiating the signal appearing at the output of adder 26.

The "main bang" signal from pulser 112a is also delivered to a "dead time" monostable multivibrator 30 in interface logic circuit 22. Multivibrator 30 will have an adjustible period which will typically be on the order of one microsecond. Multivibrator 30, when set by the "main bang" signal, will provide a gating signal to a clamp circuit 32. Clamp circuit 32, when gated, will disable the interface logic circuit 22 by pulling the output of adder 26 to ground. Thus, as briefly described above, the interface logic circuit 22 is disabled, and can not produce a synchronization pulse, until after the period of multivibrator 30 which is commensurate with the ring down time of transducer 18.

In one embodiment of the invention, the differentiator 28 comprised a very fast one-shot multivibrator while the false interface circuit 24 comprised a multivibrator having a 20 microsecond period. The purpose of the false interface multivibrator 24 is to provide a signal which, upon being processed by differentiator 28 will reset the extensometer after a sufficient amount of time has past for all echos of interest to have been received. Thus, the false interface multivibrator creates what appears to be another echo after all acoustic information has been gathered.

It will be obvious to those skilled in the art that the present invention may be electronically implemented in different ways. The essential point is that the couplant/workpiece interface is actually detected and the echo from this interface substituted for the "main bang" signal in the prior direct contact type of extensometer. This technique of the present invention, coupled with the utilization of a dry couplant that has a much shorter acoustic path length than the part to be examined, permits the successful measurement of the length or thickness of parts having rough

exposed surfaces and particularly parts positioned where access is limited. It is to be noted that the present invention may be employed with apparatus other than extensometers, thickness gages for example.

Referring to Figure 2, an embodiment of the invention is depicted wherein the couplant 18 comprises a multilayer composite or sandwich, the several layers 18a, 18b and 18c each being characterized by a different acoustic impedance. In the Figure 2 embodiment each layer of the couplant is, prior to compression, a quarter wave length thick to provide a stepped transition between the impedance Z_0 of the transducer and the impedance Z_x of the bolt. This arrangement reduces reverberation in the couplant and maximizes the echo from the far end of the bolt by enhancing energy transmission from the transducer into the bolt.

Regardless of whether a single layer or multilayer couplant is employed, the elastomer must to the extent possible match the acoustic impedance of the bolt to that of the transducer and, of course, must have the proper impedance and transmission characteristics to conduct ultrasonic energy. The couplant material must be compliant and, in accordance with the invention, should have a shorter acoustic time than the workpiece. The present invention thus comprises a method of coupling an ultrasound transducer to a rough or rounded surface wherein an elastomer couplant is placed between the transducer and the surface. The invention operates by ignoring everything that happens between the "main bang" and the receipt at the transducer of an echo from the couplant/bolt interface and enables the making of measurements which are accurate within 0.025mm.

Claims

1. A method for the non-destructive testing of workpieces comprising the steps of:

positioning a dry compliant couplant between an ultrasound transducer and a workpiece, non-planar surface features on the workpiece being embedded in the couplant whereby the transmission axis of the transducer will remain substantially transverse to a plane defined by the average surface of the workpiece;

exciting the transducer to cause generation thereby of a burst of ultrasonic energy, the ultrasonic energy being directed through the couplant into the workpiece and being reflected from inhomogeneities encountered along the transmission axis,

detecting energy reflected from inhomogeneities in the ultrasound transmission path;

identifying the echo commensurate with energy reflected from the couplant/workpiece interface,

disregarding echos received prior to identification of the echo from the couplant/workpiece interface; and

employing echos received after the identification of the echo from the couplant/workpiece interface to determine a parameter of the workpiece.

2. A method as claimed in claim 1, wherein the workpiece has an axis and wherein the transmission axis of the transducer is maintained parallel to the workpiece axis.

3. A method as claimed in claim 1 or 2, wherein the workpiece is a fastener and the parameter which is determined is elongation.

4. A method as claimed in anyone of claims 1, 2 or 3 wherein the step of identifying the echo from the couplant/workpiece interface comprises:

disabling a synchronization pulse generator during a first time period subsequent to transducer excitation commensurate with the ringing of the transducer;

enabling the synchronization pulse generator after the said first time period; and

delivering signals commensurate with all received echos to the synchronization pulse generator whereby a pulse corresponding to the reflection of energy from the couplant/workpiece interface will be provided.

5. A method as claimed in any one of claims 1 to 4 wherein the step of determining a parameter of the workpiece comprises:

measuring the time between generation of the pulse commensurate with the couplant/workpiece interface and the receipt of an echo from the side of the workpiece disposed oppositely from the couplant along the said transmission axis.

6. A method as claimed in anyone of claims 1 to 5 further comprising:

generating a reset signal after a time period commensurate with receipt of all echos of interest has elapsed, all echos received after the reset signal until identification of another couplant/workpiece interface echo being disregarded.

7. Apparatus for use in the non-destructive testing of workpieces comprising:

transducer means responsive to an excitation signal for generating ultrasonic energy, the ultrasonic energy being radiated along an axis, said transducer means also generating signals commensurate with echos corresponding to the reflection of ultrasonic energy from inhomogeneities encountered along the said axis;

dry coupling means positioned between the workpiece and said transducer means, the ultrasound energy passing through said coupling means, said coupling means being sufficiently compliant so that workpiece surface features which extended above a plane transverse to the said axis will embed therein:

first receiver means responsive to echo signals generated by said transducer means for generating information bearing signals; and

second receiver means responsive to echo signals generated by said transducer means and to transducer excitation signals for generating timing control signals, said timing control and information bearing signals enabling the calculation of workpiece parameters of interest.

8. An apparatus as claimed in claim 7 wherein said coupling means comprises:

a member comprised of an elastomeric material, said member having a Shore number in the range of 20 to 60.

9. An apparatus as claimed in claim 8 wherein said elastomeric member has a thickness of between 0.635 and 3.8mm and a Shore rating in the range of 25 to 45.

10. An apparatus as claimed in anyone of claims 7 to 9, wherein said second receiver means comprises:

means responsive to the transducer means excitation signal for generating a disabling control signal having a duration commensurate with the ring down time of said transducer means;

means responsive to echo signals generated by said transducer means for generating timing control signals; and

means responsive to said disabling control signals for disabling said timing control signal generating means whereby the first echo signal to which said timing control signal generating means will respond is the echo from the coupling means/workpiece interface.

11. An apparatus as claimed in anyone of claims 7 to 10, wherein said timing control signal generating means comprises:

means for amplifying received echo signals; and

pulse generator means responsive to amplified echo signals from said amplifier means for generating pulses commensurate with the receipt of echos from the coupling means/workpiece interface.

12. An apparatus as claimed in anyone of claims 1 to 11, further comprising:

means responsive to transducer means excitation signals for generating a reset control signal, said reset control signal being applied to said pulse generator means and causing the generation of a timing control signal at a time subsequent to the receipt of all echos of interest.

13. An apparatus as claimed in anyone of claims 10 to 12 wherein said disabling means comprises:

means for clamping the input to said pulse generator means to a reference potential.

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